

## **Using NOGAPS Singular Vectors to Diagnose Large-Scale Influences on Tropical Cyclogenesis**

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### **LONG-TERM GOALS**

The overarching goal is to improve our understanding of synoptic-scale influences on tropical cyclone (TC) formation and motion in the western North Pacific Ocean, in the context of error growth in forecast models. Benefits to the Navy would include improved forecast skill of the structure and track of developing and recurving TCs.

### **OBJECTIVES**

The first objective is to connect Singular Vector (SV) and ensemble perturbation growth to synoptic-scale dynamical influences on tropical cyclone formation and structure change. The second objective is to extend these investigations towards analysis of tropical cyclone structure in high-resolution

Report Documentation Page				Form Approved OMB No. 0704-0188	
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1. REPORT DATE <b>30 SEP 2013</b>		2. REPORT TYPE		3. DATES COVERED <b>00-00-2013 to 00-00-2013</b>	
4. TITLE AND SUBTITLE <b>Using NOGAPS Singular Vectors to Diagnose Large-Scale Influences on Tropical Cyclogenesis</b>				5a. CONTRACT NUMBER	
				5b. GRANT NUMBER	
				5c. PROGRAM ELEMENT NUMBER	
6. AUTHOR(S)				5d. PROJECT NUMBER	
				5e. TASK NUMBER	
				5f. WORK UNIT NUMBER	
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) <b>University of Miami, Rosenstiel School of Marine and Atmospheric Sciences, 4600 Rickenbacker Causeway, Miami, FL, 33149</b>				8. PERFORMING ORGANIZATION REPORT NUMBER	
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)				10. SPONSOR/MONITOR'S ACRONYM(S)	
				11. SPONSOR/MONITOR'S REPORT NUMBER(S)	
12. DISTRIBUTION/AVAILABILITY STATEMENT <b>Approved for public release; distribution unlimited</b>					
13. SUPPLEMENTARY NOTES					
14. ABSTRACT					
15. SUBJECT TERMS					
16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT <b>Same as Report (SAR)</b>	18. NUMBER OF PAGES <b>5</b>	19a. NAME OF RESPONSIBLE PERSON
a. REPORT <b>unclassified</b>	b. ABSTRACT <b>unclassified</b>	c. THIS PAGE <b>unclassified</b>			

models, via initialization of a realistic balanced vortex. The goal is to extend these methodologies into the Navy's COAMPS-TC framework, and to make available for use to a variety of collaborators for their own scientific and quasi-operational testing.

## **APPROACH**

Several sensitivity and predictability studies have been completed. The approach has been to investigate perturbation growth in SVs and in ensemble predictions, for cases from ONR's Tropical Cyclone Structure (TCS-08) field experiment.

The sensitivity patterns, evolving horizontal and vertical structure and error growth associated with SVs have been investigated. The connection between perturbation structures and synoptic-scale processes influencing TCs has been explored. Hypotheses for SV growth have been formulated and published by Munehiko Yamaguchi, the graduate student funded on this grant, using a barotropic model with idealized vortices and initial conditions from the TCS-08 case of Typhoon Sinlaku.

A highly configurable vortex initialization method based on theory and observations has been designed to rapidly provide initial estimates of TC structure in high-resolution models, for TC initialization and predictability studies. A manuscript on this method and the sensitivity of numerical simulations to the prescribed initial vortex has been accepted and is in press in *Monthly Weather Review*. In the past year, the software has been converted from MATLAB to FORTRAN and has been transitioned for use by Navy researchers and collaborators.

## **WORK COMPLETED**

The research on Singular Vectors has been described in previous Annual Reports, and is now published in *Mon. Wea. Rev.* and *J. Atmos. Sci.* (Yamaguchi and Majumdar 2010; Yamaguchi et al. 2011). We expect that the results produced from this study will be important in identifying processes associated with error growth in models such as COAMPS-TC. Yamaguchi received his Ph.D. in 2011.

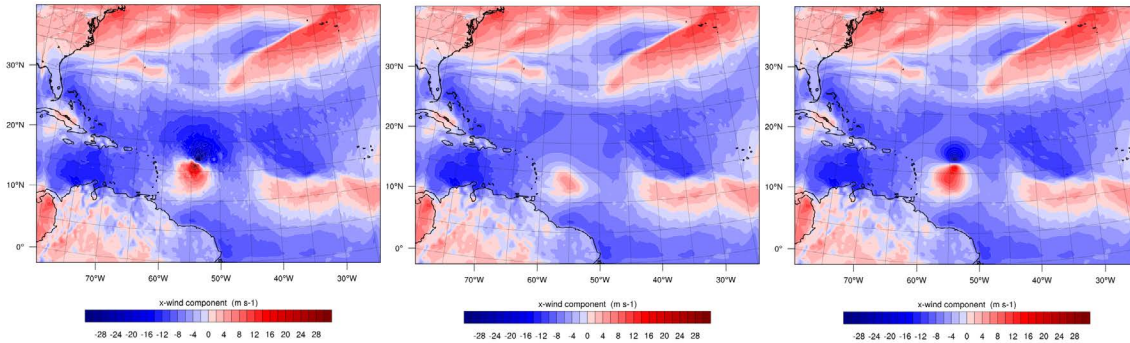
The configurable framework for vortex initialization was initially developed in MATLAB, and has now been debugged and fully converted to FORTRAN. The motivation is to offer flexible, modular software to be used by the community for a variety of predictability and sensitivity studies, and to provide a benchmark upon which high-resolution data assimilation schemes must improve. Software to remove the vortex, similar to the operational version at the Geophysical Fluid Dynamics Laboratory (GFDL, Kurihara et al. 1995), has been completed in both MATLAB and FORTRAN, together with different configurations of the radial and vertical structure of the vortex comprising a primary and secondary circulation. A manuscript has been accepted for publication in *Monthly Weather Review* (Rappin et al. 2013). The summary below focuses on this part of the research, which has been conducted using remaining funds on a no-cost extension of the grant in 2013.

## **RESULTS**

The conversion of the extensive vortex removal and initialization software from MATLAB to FORTRAN was necessary in order for the code to be efficient, portable and flexible with I/O in various formats from different models. The FORTRAN version, which is 200 times faster than the MATLAB version of Rappin et al. (2013), has now been fully transitioned for use by NRL Monterey. Brian McNoldy, the Senior Research Associate who has performed the software conversion, visited

NRL Monterey to introduce NRL scientific staff to the modular software and to discuss collaborative ideas.

The vortex initialization framework allows for over 20 different specifications of flow in the boundary layer and free atmosphere, with users being able to seamlessly introduce their own configurations in the modular FORTRAN code. The radial and vertical profiles in the free atmosphere, and the boundary layer configuration are described briefly in the 2012 Annual Report, and in greater depth in Rappin et al. (2013). An example of a more realistic and intense initial vortex is given in Fig. 1.



**Figure 1. Example showing zonal winds in the vortex removal and configuration process, for an Atlantic hurricane. Left: Original analysis field. Middle: background flow after removal of original vortex. Right: New idealized symmetric vortex added to the background flow.**

Rappin et al. (2013) raised several issues that are common in vortex initialization and data assimilation. Over the past year, we have investigated them further in order to diagnose the problems and suggest solutions. One concern is the inevitable spin-down of the vortex in the first 12h after initialization, as the vortex adjusts physically and dynamically to the model. We suspect that this is partially due to the inconsistency between the idealized boundary layer scheme presently being used in the vortex configuration, and the boundary layer scheme in the full-physics numerical model (which can be WRF or COAMPS-TC). Some candidates for simplified boundary layer models that better approximate those in the full-physics model have been identified. Additionally, the maintenance of deep convection in the vortex is being investigated.

A major effort over the past year has been to permit forward integrations of the initial field including the configurable vortex with an updated numerical model. For this purpose we selected WRF Version 3.5, which was released in 2013. However, due to a variety of roadblocks including substantial undocumented changes in WRF, and an entire overhaul of the local supercomputing cluster in Miami resulting in a delay and compiling issues, progress ended up not being as seamless as anticipated. These roadblocks have now been overcome, and the transition to a new model version and computing system now allows for a much higher resolution version for numerical experiments than had been manageable in Rappin et al. (2013). The resolution of choice for the numerical experiments is a fixed 27 km outer domain, with two-way feedback within the inner storm-following nests of 9 and 3 km grid spacing.

Several sensitivity experiments are now underway. These include the sensitivity to vortex size (via variation of the radial structure configuration), and the vertical structure. For different initial

configurations of the vortex, the numerical model will be integrated forward and compared with the synthetic ‘nature run’. This work will continue with a goal of a new publication in the peer-reviewed literature in 2014, even though the formal part of the project has concluded.

## **IMPACT/APPLICATIONS**

The scientific impact will be an improved understanding of the underlying environmental and internal mechanisms that influence tropical cyclone evolution. This understanding will be coupled with a quantitative knowledge of error growth in models. High-resolution simulations, vortex initialization and examination of perturbation growth will be performed in collaboration with the COAMPS-TC team at NRL Monterey, leading to improved Navy forecasts of TC structure.

## **TRANSITIONS**

The full vortex removal and initialization software has been transitioned onto NRL’s computing system. The computationally efficient software will allow for a range of studies using COAMPS-TC, including the well-recognized ‘spin-down’ problem, and advancing initialization and assimilation to yield improved specifications of tropical cyclone size, secondary circulation, and behavior in a sheared environment.

A preliminary version of the vortex configuration software has been used by Dr William Lewis at the University of Wisconsin, for his own vortex initialization and assimilation studies as part of a NOPP project (PI: C. Velden, CIMSS/University of Wisconsin).

Additionally, the software has been transferred to Prof. Steven Cavallo of the University of Oklahoma, who is investigating polar vortices as part of his ONR-funded research under the Young Investigator Program. He is investigating the response of the polar and mid-latitude atmospheric circulation to differences in the structure of the polar vortex.

## **RELATED PROJECTS**

This project is related to the TCS-08 grant N000140810251: “Advanced Satellite-Derived Wind Observations, Assimilation, and Targeting Strategies during TCS-08 for Developing Improved Operational Analysis and Prediction of Western North Pacific Tropical Cyclones”, on which Majumdar is a Co-PI. The NOGAPS Singular Vectors are also being investigated in this grant (see 2012 report from this grant, PI Velden). The high-resolution vortex initialization tools developed as part of this project are being used in the collaborative NOPP grant between the PI and CIMSS Wisconsin, NRL Monterey and NCAR, on assimilating satellite data to improve forecasts of TC intensity change.

## **PUBLICATIONS**

Majumdar, S. J. and P. M. Finocchio, 2010: On the ability of global Ensemble Prediction Systems to predict tropical cyclone track probabilities. *Wea. Forecasting*, **25**, 679-700.

Rappin, E. D., D. S. Nolan and S. J. Majumdar, 2013: A highly configurable vortex initialization method for tropical cyclones. *Mon. Wea. Rev.*, in press.

Yamaguchi, M. and S. J. Majumdar, 2010: Using TIGGE data to diagnose initial perturbations and their growth for tropical cyclone ensemble forecasts. *Mon. Wea. Rev.*, **138**, 1635-3655.

Yamaguchi, M., D. S. Nolan, M. Iskandarani, S. J. Majumdar, M. S. Peng and C. A. Reynolds, 2011: Singular vectors for tropical cyclone-like vortices in a nondivergent barotropic framework. *J. Atmos Sci.*, **68**, 2273-2291.

## **HONORS/AWARDS/PRIZES**

2013: PI Majumdar was assigned as Co-Chair of the American Meteorological Society's annual conference on Integrated Observing and Assimilation Systems for the Atmosphere, Oceans and Land Surface (IOAS-AOLS), held at the AMS Annual Meeting.

2013: PI Majumdar was appointed Director of the Graduate Program in Meteorology and Physical Oceanography, and elected Chair of the RSMAS Graduate Academic Committee. [The successes of students on ONR TCS-08 grants made this possible]